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Short and long-term energy intake patterns and their implications for human body weight regulation

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HIGHLIGHTS

- Body weight is relatively stable despite large daily variations in food intake.
- Over the years, millions of kilocalories are consumed but only thousands are stored.
- Mathematical models show that body weight regulation may not require precise control of day-to-day food intake.
- We describe promising new methods to monitor diet adherence and control body weight.

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ABSTRACT

Adults consume millions of kilocalories over the course of a few years, but the typical weight gain amounts to only a few thousand kilocalories of stored energy. Furthermore, food intake is highly variable from day to day and yet body weight is remarkably stable. These facts have been used as evidence to support the hypothesis that human body weight is regulated by active control of food intake operating on both short and long time scales. Here, we demonstrate that active control of human food intake on short time scales is not required for body weight stability and that the current evidence for long term control of food intake is equivocal. To provide more data on this issue, we emphasize the urgent need for developing new methods for accurately measuring energy intake changes over long time scales. We propose that repeated body weight measurements can be used along with mathematical modeling to calculate long-term changes in energy intake and thereby quantify adherence to a diet intervention and provide dynamic feedback to individuals that seek to control their body weight.

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1. Introduction

Humans consume food episodically in the form of meals and snacks. In contrast, a continuous supply of energy is required to maintain life and perform physical work. Therefore, even weight-stable humans are practically always in a state of energy imbalance. When we discuss human body weight regulation as a problem of energy balance [1], there is an implicit assumption of time averaging. What is the relevant time scale over which energy is balanced in weight stable people? This basic question has been neglected despite its fundamental role in understanding human body weight regulation.

Here, we explore the question of how short and long-term patterns of energy intake affect body weight using mathematical modeling of human metabolism. We demonstrate that the relevant time scale of human energy balance is many months and that body weight is remarkably stable despite large random daily fluctuations in food intake. However, relatively small persistent changes in energy intake can have a substantial effect on body weight over long time scales, although not as large as was previously believed. We show how the sensitivity of body weight to long-term changes in energy intake can be harnessed to provide accurate estimates of changes in free-living energy intake using repeated body weight measurements. Furthermore, such methods allow for monitoring adherence to a lifestyle intervention and the possibility of dynamic model-based feedback control of body weight.

2. Short-term energy intake fluctuations have little effect on body weight

In his classic 1927 metabolism textbook, Eugene Dubois states that “there is no stranger phenomenon than the maintenance of a constant body weight under marked variation in bodily activity and food consumption” [2]. For example, free-living energy intake is known to vary

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from day to day by 20–30% while body weight fluctuates relatively little [3].

Mathematical models of human energy balance and body weight dynamics have demonstrated that small body weight fluctuations are expected even with relatively large random day-to-day variations of energy intake [4–7]. For example, the gray curve in Fig. 1A illustrates the large fluctuations in energy intake of a subject who participated in the Beltsville one year dietary intake study [8]. The black curve in Fig. 1A illustrates the estimated energy expenditure in this subject using a computational model of human macronutrient metabolism and body composition dynamics [9]. Despite repeated daily energy imbalances amounting to several hundred kilocalories, Fig. 1B shows that the measured and simulated body weight fluctuations were small.

In Appendix A, we use a simplified mathematical model of human body weight dynamics to show that the standard deviation of the body weight fluctuations is a decreasing function of a parameter ε representing how energy expenditure varies with body weight. Greater body weight fluctuations are expected when the energy expenditure versus body weight curve is shallower. We previously estimated that the average adult has ε ≈ 22 kcal/kg/day [10] and we show in Appendix A that weight variations on the order of 1 kg correspond to random, uncorrelated, daily energy intake variations on the order of 630 kcal/day. Even for a conceivably low value of ε = 10 kcal/kg/day for an extremely sedentary person, day-to-day food intake variations of ~400 kcal/day are required to result in body weight fluctuations of 1 kg. Therefore, body weight is remarkably stable in the face of random, uncorrelated fluctuations in energy intake.

The reason why body weight fluctuations are small in comparison to variations in energy intake and physical activity is that the slope of the relationship between energy expenditure and body weight causes human weight change to operate on a very slow characteristic time scale. Therefore, the day-to-day fluctuations in food intake are effectively averaged over a long time. By the law of large numbers, the expected standard deviation in the body weight is reduced by a factor proportional to the square root of the averaging time in comparison to the standard deviation of the energy intake. Note that if the energy intake time course exhibits significant autocorrelations, the fluctuations of body weight will become more prominent.

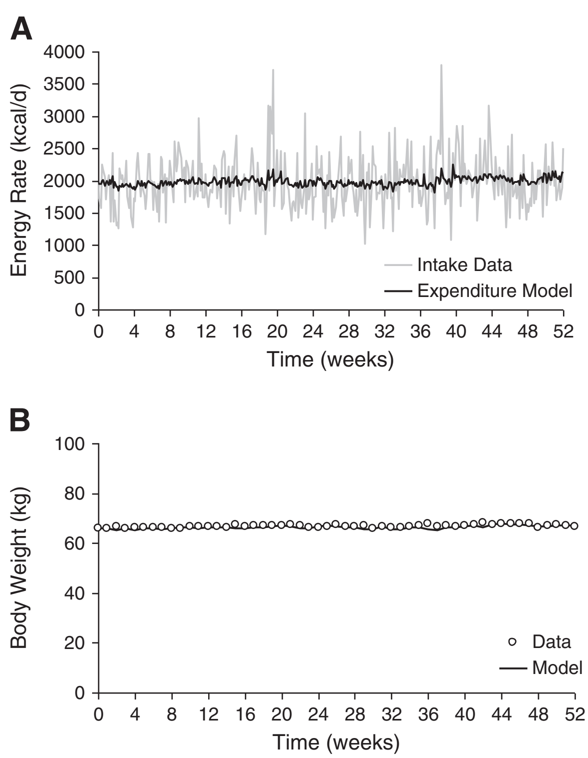

Fig. 1. Large daily fluctuations of energy intake and energy balance lead to little variation of body weight. (A) Daily energy intake data and computer simulated energy expenditure of a participant in the Beltsville one year dietary intake study [8]. (B) Weekly body weight data and computational model simulations illustrating the relative stability of body weight.

3. Is human energy balance actively regulated through control of food intake?

Weight stability despite large food intake fluctuations might be misinterpreted to imply the existence of a highly sensitive feedback control system whereby each day's food intake is adjusted to compensate for previous energy imbalances. However, mathematical models demonstrate that active control of food intake is not necessary to explain the stability of body weight in the face of large, uncorrelated, day-to-day energy intake fluctuations. Rather, the long term average energy intake will be stable if fluctuations are uncorrelated such that intake on one day is not significantly influenced by the intake on the day before. In other words, body weight regulation does not require active control of food intake operating on a short time scale.

Another argument for active control of food intake emphasizes the long-term stability of body weight in comparison to the cumulative energy consumed and was articulated by eminent obesity researcher Jeffery Friedman: "The average human consumes one million or more calories per year, yet weight changes very little in most people. These facts lead to the conclusion that energy balance is regulated with a precision of greater than 99.5%" [11]. This example compares the energy content of typical yearly weight gain (about 0.5 kg or 4000 kcal) with the cumulative energy consumed in a year (about 1 million kcal). Unfortunately, this calculation ignores the dynamic adaptations of energy expenditure as body weight is gained that act to counter a persistent increment in energy intake [12]. As has been previously demonstrated [13], without properly accounting for energy expenditure changes, very small persistent increases in energy intake have been erroneously calculated to generate unrealistically huge weight gains over extended time periods. Since such enormous weight gain clearly does not typically occur, this may be mistaken as evidence in support of active control of human energy intake.

When correctly accounting for energy expenditure adaptations, what is the expected long-term weight gain for a persistent change in energy intake? For a person maintaining their average body weight, the long-term mean energy intake equals the long-term mean energy expenditure which is proportional to the body weight. Hence, long-term changes in body weight are related to persistent changes in energy intake by the relation $\Delta I = \varepsilon \Delta W$ and the new equilibrium weight takes several years to be achieved [12]. Hence, to maintain weight within 1 kg over several years requires that the long-term average energy intake must be accurate to within about ε = 22 kcal/day.

Active control of food intake may be required to limit the long-term drift in energy intake — especially in the face of a dramatic change in the food environment. Is there evidence for such active control of long-term food intake in humans? A decades-long natural experiment provides equivocal evidence. Since the 1970s, U.S. per capita food availability increased by roughly 750 kcal per day whereas average adult increased their energy intake by only about 250 kcal/day over this time period [10]. In other words, the dramatic increase in availability and marketing of highly palatable, convenient, inexpensive, and energy-dense foods may have been actively resisted since only about one third of the increased food available was actually eaten. Thus, these data might be interpreted as evidence that there is active control of human food intake. However, it is unclear exactly how much of an increase in average energy intake would have been expected if there was no active control.

Following periods of experimental overfeeding in humans, ad libitum energy intake generally returns to baseline without an appreciable undershoot as might be expected if food intake was actively controlled [14–17]. However, a substantial degree of hyperphagia was observed